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This is the first annual report describing research at the University of Illinois at Urbana-Champaign, aimed at establishing the feasibility of producing parts to net or near-net shapes starting with Rheocast preforms by forging-type, THIXOFORGING, operations.

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ABSTRACT

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1 ten to the 7th power

FOREWORD

Technical monitor of the contract was Mr. R. Gagne.

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ABSTRACT

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Ingots of Sn-15%Pb alloy and aluminum alloys 6061 and A356 were heated to temperatures above liquidus and in the liquid-solid range. The partially solidified charge, Rheocast, materials were previously made in a continuous slurry producer. Sound flanged shaped cup parts with good mechanical properties and unidirectionally solidified cylinders were produced in a 50 ton hydraulic press.

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I. INTRODUCTION

Fundamental and applied research in the past five years has led to the finding that certain metal forming operations can be carried out using a partially solid charge material provided the solid present is particulate and spheroidal in shape; it is non-dendrite [1-5]. In the work presented here, the possibility of exploiting the special metallurgical structure and rheological behavior of a partially solidified alloy in a forging-type operation was investigated, and the results were compared to conventional liquid metal forging. The effect of process variables during forging of both liquid and partially solid aluminum alloys on the structure and properties of components produced and on the die thermal behavior was studied. Computer simulation work on heat flow was carried out to determine the effect of applied pressure during the forging operation on the heat transfer coefficient at the die-metal interface.

Shaping of liquid metals by forging-type operations has been described under a variety of names such as squeeze casting, liquid metal forging, extrusion casting and liquid stamping. The basic process steps are as follows. A measured amount of liquid metal is poured into the lower cavity of an open die set. After partial solidification of the outer extremity of the charge, the two die halves are brought together to form the part. Solidification is then completed under a predetermined hydrostatic pressure. While the process is relatively new in the U.S.A., it had been extensively investigated and used in the U.S.S.R. and to a lesser degree in Japan.

Various investigators have reported substantial improvements in microstructure (e.g., porosity) and mechanical properties over conventional castings when solidification is carried out under a direct applied pressure. Plyatskii

[6] has reported improvements in bend and tensile strengths of cast iron solidified under a pressure of ~ 2×10^6 Pa. Nishida and Suzuki [7] studied the effect of applied pressure on gas porosity in aluminum castings and report that a pressure of ~ 5×10^7 Pa resulted in complete disappearance of all macroscopic porosity. They attribute this observation to increased solubility of hydrogen in the solid with increasing applied pressure. Suzuki, et al. [8-11] have reported significant improvements in tensile and impact strength, ductility, fatigue and wear properties of Al-(2-22%)Si alloys solidified under pressures of up to ~ 3×10^8 Pa. Similar results were obtained in other aluminum alloys [12] and copper base alloys [13, 14]. Other investigators have reported increased solid solubility of Si in aluminum [15, 16] and changes in solidification temperature range [7, 16-19] due to the applied pressure. Shorter local solidification times due to an increase in metal-die heat transfer coefficient with applied pressure has also been postulated [20].

Shaped components of a variety of alloys including aluminum, copper and steel alloys have been produced via liquid metal forging. Plyatskii [6] has reported production of drill bit collars, engine compressor parts and turbine blades. Bidulya, et al. [21, 22] have discussed the process variables in production of a 321 stainless steel hub (~ 52 Kg) and various modes of die failure. Recent work in production of shaped parts in the U.S.A. has also been reported [23-25].

The important liquid forging process parameters noted in the above studies include the following:

(a) melt and die temperatures;

(b) die material and die coating;

(c) dwell time of charge in the die before pressurization; and

(d) magnitude and duration of applied pressure.

A common feature of the various techniques used in producing shaped components via liquid forging is partial solidification of the charge in the die cavity prior to application of pressure. Earlier fundamental studies on partially solid metal slurries has shown that the structure, viscosity and thixotropic behavior of these materials can be especially designed by proper manipulation of process variables during slurry production [4]. The thixotropic behavior of the partially solid charge should reduce metal handling, transfer and metering problems normally associated with liquid forging. Furthermore, the shear rate dependence of charge viscosity should permit development of a net shape forming process more akin to solid metal forging processes under significantly reduced applied pressures.

While it is generally recognized that pressurization during solidification enhances heat transfer across a metal-die interface, little experimental and theoretical work has been carried out to investigate this phenomenon. The heat transfer coefficient would affect die thermal behavior, hence die failure, in important ways. In the work described herein thermal data obtained from thermocouples located in the die and forgings were combined with a one-dimensional computer heat flow model to determine the effect of applied pressure on the aluminum alloy - steel die heat transfer coefficients.

II. APPARATUS AND PROCEDURE

The apparatus for forging of liquid and partially solid charge materials, shown in Figure 1, consists of: (a) a resistance furnace; (b) a controlled pressure penetrometer for monitoring the charge material characteristics; (c) a 50 ton Wabash hydraulic press containing a controlled temperature die set; and (d) temperature measurement and control devices.

The resistance furnace for reheating, partial or complete melting, of the charge material is shown on the left side of Figure 1(a) and consists of a vertical cylindrical chamber, 0.06 m in diameter and 0.12 m long. Its temperature is controlled to ± 1°K. The charge material located in an alumina crucible can be moved out of the furnace by a hydraulic jack located below it. The penetrometer consists of a 3.2×10^{-3} m diameter alumina rod attached at one end to a small air cylinder. The lower end of the penetrometer rests on top of a slug of the charge material and exerts a controlled amount of pressure on the slug. It is calibrated to penetrate slugs of partially solid materials at a given velocity when the slugs reach a desired volume fraction solid during the heating cycle. Calibration, pressure setting, was done by locating two thermocouples in the slug, one near the center and one close to the edge. During reheating cycle of the various partially solid charge materials, the penetrometer was the primary control for determining when the charge was ready for the forging operation. The temperature in superheated liquid charge materials was monitored by a thermocouple located in the alloy. Once a charge material was deemed ready for the forging operation, it was manually transferred to the lower cavity of the die in the hydraulic press.

The H-19 steel dies were used to produce a flanged cup shaped part and a unidirectionally solidified cylindrical shaped part, see Figure 2. The dies were preheated to the desired temperature via six 1000 watt cartridge heaters located in the lower die, and a smaller heater snugly fitted inside the upper die. Die temperature was closely controlled via a control device coupled to the heaters. An H-13 steel ejector cylinder was machined and located at the bottom of the lower die. Thermocouples were press fitted in this piece at distances of 10^{-3}, 9×10^{-3} and 15×10^{-3} meters from the metal-die interface.

The charge materials used were a model low temperature Sn-15%Pb alloy and two commercial aluminum alloys; 6061 and A356. The alloys for forging in the liquid-solid range were prepared in a continuous slurry production (rheocasting) machine previously described [2, 5].

The die coating used for the tin-lead alloys was molybdenum disulfide aerosol spray, while an oil graphite mixture was generally used for the aluminum alloys. In the unidirectional solidification experiments, the sides of the lower die and the bottom of the top die were lined with fiberfrax paper and cement. Two or three thermocouples were located inside the cavity at various distances from the metal-die interface, see Figures 2(c) and 2(d).

The volume of the charge material in each experiment was 85×10^{-6} m^3. After introduction of the charge in the lower die half, the dies were closed at a speed of ~ 0.018 m/sec. The process variables studied were temperature or volume fraction solid of the charge material, die temperature and applied pressure. Due to the speed limitations of the present apparatus, no special effort was made to study the effect of shear strain and dwell time. Two types of parts were produced, a flanged cup and a unidirectionally solidified cylinder.

Parts produced were subjected to normal metallographic examination. Several tensile specimens were machined from the 6061 aluminum alloy flanged cups. These were heat treated, solutionized 13 hours at 520°C and aged 8 hours at 175°C, and tested for tensile properties.

III. RESULTS AND DISCUSSION

A. Cup Shaped Parts

Figure 3 shows photographs and a representative microstructure of Sn-15%Pb alloy part. The volume fraction of solid, g_s, in the initial charge was ~ 0.5 -- its temperature was 465°K. The larger spheroidal particles in Figure

3(b) were those existing in the charge prior to pressurization. The darker matrix is the eutectic liquid that solidified last. The measured temperature profiles in the die, at 10^{-3}m from the metal-die interface, are shown in Figure 4. In order to distinguish between forgings produced from completely liquid and partially solid initial charge materials, the latter will hereafter be referred to as thixoforging -- forging of a thixotropic charge material.

The microstructures of flanged cups produced from partially solid and liquid 6061 aluminum alloy charge materials are shown in Figure 5. Figure 5(a) shows the characteristic structure of a thixoforged material. Each grain resulted from coarsening of a primary solid particle in the initial slurry. The dendritic structure of Figure 5(b) is that expected from conventional solidification of a completely liquid charge.

The thermal response of the dies as a function of the time during forging of liquid and partially solid 6061 aluminum alloy is shown in Figure 6. For each charge material, the die temperature increases as soon as the metal is poured into the die cavity. For the thermocouple located at 10^{-3}m from the die surface, the rate of temperature increase rises sharply when the dies close and the pressure builds up. The pressurization times, about 8 seconds after pouring, are shown by the arrows in Figure 6. The die temperature further increases after pressurization until a maximum is reached, then it drops. The thermocouples located at 5×10^{-3} and 9×10^{-3}m respond similarly; however, their response is considerably slower and they do not show the sharp change in temperature profile at the pressurization time. Furthermore, the maximum temperature attained at each thermocouple decreases as the distance from the interface increases. The temperatures of all the thermocouples eventually become the same and then gradually decrease to the initial die temperature

of ~ 673°K. Finally, the rate and amount of the temperature increase of the die depends on the process variables and on the nature of the charge, as discussed below.

1. Partially Solid versus Liquid Charge

The measured die temperatures during production of flanged cup parts of Sn-15%Pb alloy and 6061 aluminum alloy are shown in Figures 4 and 6, respectively. The lower die temperatures recorded when partially solid charge materials were used are due to their lower temperatures and heat contents.

2. Initial Die Temperature

The effect of initial die temperature on thermal profiles during the casting cycle were investigated. It was found that the relative change in die temperature could be lowered by increasing the initial die temperature. The limitations of the press speed in the apparatus necessitated the use of relatively high initial die temperatures (about 673 to 773°K for the aluminum alloys).

3. Applied Pressure

The effect of applied pressure on die thermal behavior was studied on superheated (50°K) 6061 aluminum alloy charge material. Figure 7 shows results obtained with die pressures of 6.1×10^7 and 13.7×10^7 Pa, respectively. As expected, increasing the applied pressure increased the heat transfer coefficient at the metal-die interface, resulting in a corresponding increase in recorded die temperatures. However, the effect of increased pressure on die thermal response is expected to level off at higher pressures. It should be noted that measured maximum die temperatures in Figure 7 are lower than those shown in Figure 6. This apparent contradiction is due to variations of the process variables in these two sets of experiments, i.e., initial die temperatures and different die coatings.

B. Unidirectional Castings

A set of unidirectional heat flow experiments were carried out with the A356 aluminum alloy. These were specifically designed to permit determination of heat transfer coefficients at the metal-die interface using a one-dimensional computer heat flow model. All process variables except those noted in the figures were kept constant during these experiments.

1. Thermal Measurements

A typical example of measured temperature profiles in both the thixo-forging and the die are shown in Figure 8. The vertical arrow in this figure indicates time of pressurization. Thermocouple locations are shown in the schematics of Figure 2(c) and (d). The thermocouples located near the forging-die interface (on both sides of the interface) show a rapid response to pressurization. The die thermocouple recorded a rapid temperature increase while the thermocouples located in the forging responded by a corresponding temperature decrease after a short delay time. Slopes of the temperature curves were measured using an expanded time scale like that shown in Figure 9. It was found that the rates of temperature change with time in the die thermocouple, located at 1 mm, were $2^{o}K/sec$ and $22^{o}K/sec$ before and after pressurization.

The die thermal behavior, at the given applied pressure, for liquid and partially solid charge materials was determined, Figure 9. The die thermal response to the liquid charge is more pronounced. The microstructures of these two castings are shown in Figure 10. No porosity was observed in these components at a magnification of 250X -- the dark spots on the photomicrographs are etching effects.

2. Computer Heat Flow Calculations

A unidirectional computer heat flow program similar to that previously reported [26] was developed to permit indirect determination of heat transfer

coefficients prior to and after pressurization of different charge materials. The geometry, dimensions, and coordinate system of both the computer model and the forging design are shown in Figure 11. The computer program employs a finite one dimensional model of the general heat flow equation which is solved using a forward difference technique.

A number of physical assumptions have been incorporated in the heat flow model to simplify the solution of the problem. They are:

1) The die is filled instantaneously.
2) When employed, pressurization commences instantaneously after a fixed, finite time following die filling.
3) The die is initially at uniform temperature and undergoes no solid state transformations upon heating.
4) The physical properties of liquid metal are independent of temperature.
5) Heat flow at the metal-die interface is characterized by a surface heat transfer coefficient, h, which changes only at the time of pressurization.
6) Convective cooling of the die assembly at the outer die surface is governed by a heat transfer coefficient, h_b, which is independent of time.

The mathematical problem can be represented by the one dimensional thermal diffusion equation:

$$k \frac{\partial^2 T}{\partial x^2} = \frac{\partial H}{\partial t} \qquad (1)$$

where H, T, t, and k represent the enthalpy, temperature, time and thermal conductivity, respectively. The boundary and initial conditions employed are:

1) $x = L_C$; $\frac{\partial T}{\partial x} = 0$ (from symmetry)

2) $x = -L_D$; $\frac{\dot{Q}}{A} = h_B \Delta T_B$

3) $x = 0$; $\frac{\dot{Q}}{A} = h \Delta T_s$

4) $t = 0$, $0 < x < L_C$; $T = T_0$

5) $t = 0$, $-L_D < x < 0$; $T = T_D$

where T_D and T_0 are the initial die and metal temperatures, respectively, and ΔT_B and ΔT_s are the temperature differences across the outer die surface and the metal-die interface. The ratios $\dot{Q}/A$ represent the rate of heat flow through a perpendicular surface of unit area. L_D and L_C are the die thickness and forging half thickness, respectively. Each of the above parameters are shown in Figure 11.

The computer program employs these equations and the boundary conditions reduced to finite difference form. In addition, the program incorporates functions which interrelate temperature and enthalpy for both the steel die and the A356 aluminum alloy. The details of these features are presented in the Appendix. Finally, the computer program was processed using an IBM 360 digital computer.

3. Simulation Results

Numerous thermal simulations were conducted in order to obtain agreement between the computer predicted temperature curves and the experimentally determined temperature profiles. In order to accomplish this, it was necessary to abruptly alter the value of the interface heat transfer coefficient, h, at the time of pressurization. The results of the thermal

simulation are compared with the experimentally measured temperatures in Figures 12 and 13 for the forging of fully liquid and partially solid (volume fraction solid ~ 0.5) A356 aluminum alloy.

For the fully liquid metal, the agreement between the two sets of curves is good, particularly at 1 and 9 mm from the interface, see Figure 12. The two values of the interface heat transfer coefficient, h_I and h_{II}, applicable before and after pressurization, respectively, were 3.4×10^3 $W.m^{-2}{}^oK^{-1}$ and 3.4×10^4 $W.m^{-2}{}^oK^{-1}$. Similarly, for the partially solid aluminum alloy, the agreement between the measured and simulated profiles is good for times less than ~ 27 seconds, see Figure 13. For this case, the values of h_I and h_{II} are 8.4×10^2 $W.m^{-2}{}^oK^{-1}$ and 3.1×10^4 $W.m^{-2}{}^oK^{-1}$. For longer times it was difficult to maintain good agreement between experiment and simulation due to radial heat losses in the die which could not be incorporated in the one dimensional model.

For both casting simulations, Figures 12 and 13, the onset of pressurization is accompanied by at least an order of magnitude increase in the value of the interface heat transfer coefficient. This finding reflects the increased contact area between the charge and the die as the pressure across the interface is increased. Similarly, the initial value of the interface heat transfer coefficient, h_I, for the partially solid charge is only 25% of the value of h_I applicable during the forging of fully liquid metal. The reduced value of h_I for the partiably solid charge is due its higher viscosity, and hence reduced contact area prior to pressurization.

C. Mechanical Properties

Flanged cup parts made from both liquid and partially solid 6061 aluminum alloy charge material were sectioned, heat treated and tested for tensile

properties. Average tensile data from several specimens are listed in Table I. These data show that even with the limitations of the hydraulic press used, the parts made can be heat treated and possess relatively good tensile properties.

CONCLUSIONS

1. The feasibility of producing parts from a partially solid thixotropic charge material in a forging-type operation was demonstrated. Flanged cup shaped parts were produced from both liquid and partially solid Sn-15%Pb and aluminum alloy charge materials.

2. Die thermal response to solidification under pressure was studied under a variety of processing conditions. A one-dimensional computer heat flow model was developed and used to correlate measured temperature profiles with predictions based on various metal-die heat transfer coefficients.

3. Relative rise in die temperature increases with increasing initial charge temperature and with increasing applied pressure.

4. There is an abrupt change in the metal-die heat transfer coefficient due to pressurization. Applied pressure of 9.1×10^7 Pa increases the heat transfer coefficient of an aluminum alloy liquid charge material from 3.4×10^3 $W.m^{-2}.^oK^{-1}$ to 3.4×10^4 $W.m^{-2}.^oK^{-1}$. The corresponding change for a partially solid initial charge material is 8.4×10^2 $W.m^{-2}.^oK^{-1}$ to 3.1×10^4 $W.m^{-2}.^oK^{-1}$.

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APPENDIX

Values of Material Properties Used in the Computer Simulation

Density The values of density for the H-13 or 19 steel die and the aluminum alloys are 7800 and 2700 kg/m^3.

Thermal Conductivity

Steel = 33.5 watt/m^oK

Aluminum = 167.4 watt/m^oK

Enthalpy The variation of enthalpy, H in cal/gm, with temperature for both the steel die and the aluminum was represented by a series of linear approximations.

Steel $H = 0.163T - 6.231$

Aluminum A356 $H = 0.258T - 12.890$

$T < 835^oK$

$H = 2.200T - 1104.400$

$835^oK < T < 885^oK$

$H = 0.262T + 81.384$

$T > 885^oK$

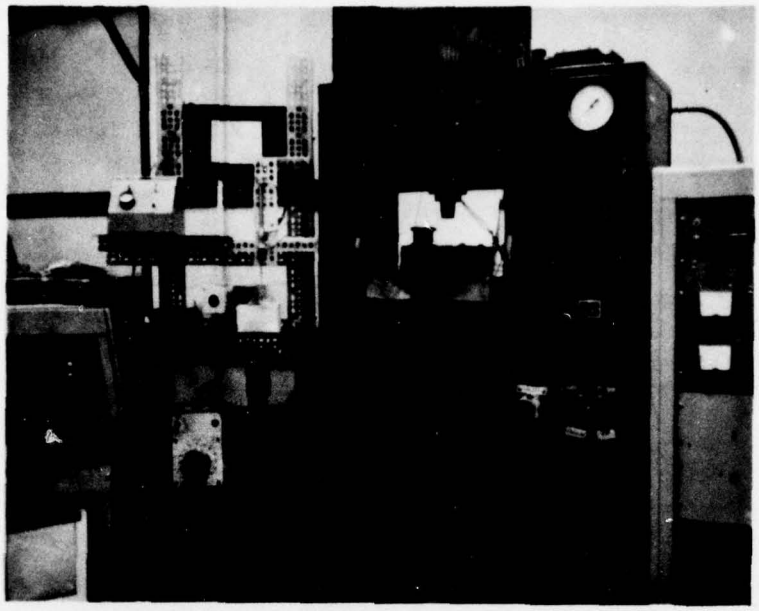
TABLE I

Tensile Properties of Heat Treated
6061 Aluminum Alloy Flanged Cup Parts*

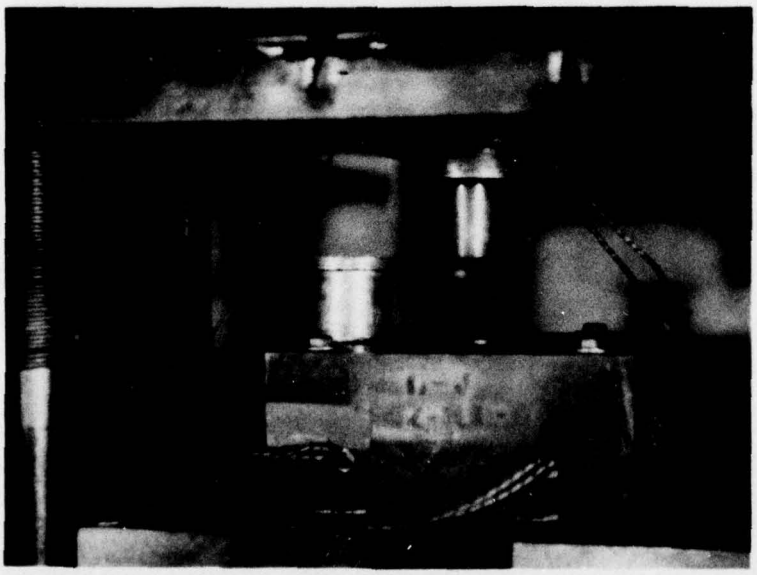
Charge	Die Temp. ^{o}K	Y.S. (MPa)	UTS (MPa)	% Elongation**
Original Rheo-cast Ingot		165	207	4
Thixoforged	723	152	214	7
Thixoforged	773	172	252	18.5
Liquid ($50^{o}K$ Superheat)	773	200	252	9

* Die pressure of 9.1×10^{7} Pa (30 tons).

** in 1.3 cm section.



[a]



[b]

Figure 1 Photographs of apparatus for forging of partially solidified alloys into shapes. (a) Overall view of the apparatus including slug reheating furnace, penetrometer, hydraulic press, and controllers, (b) the two die halves and the flanged cup produced.

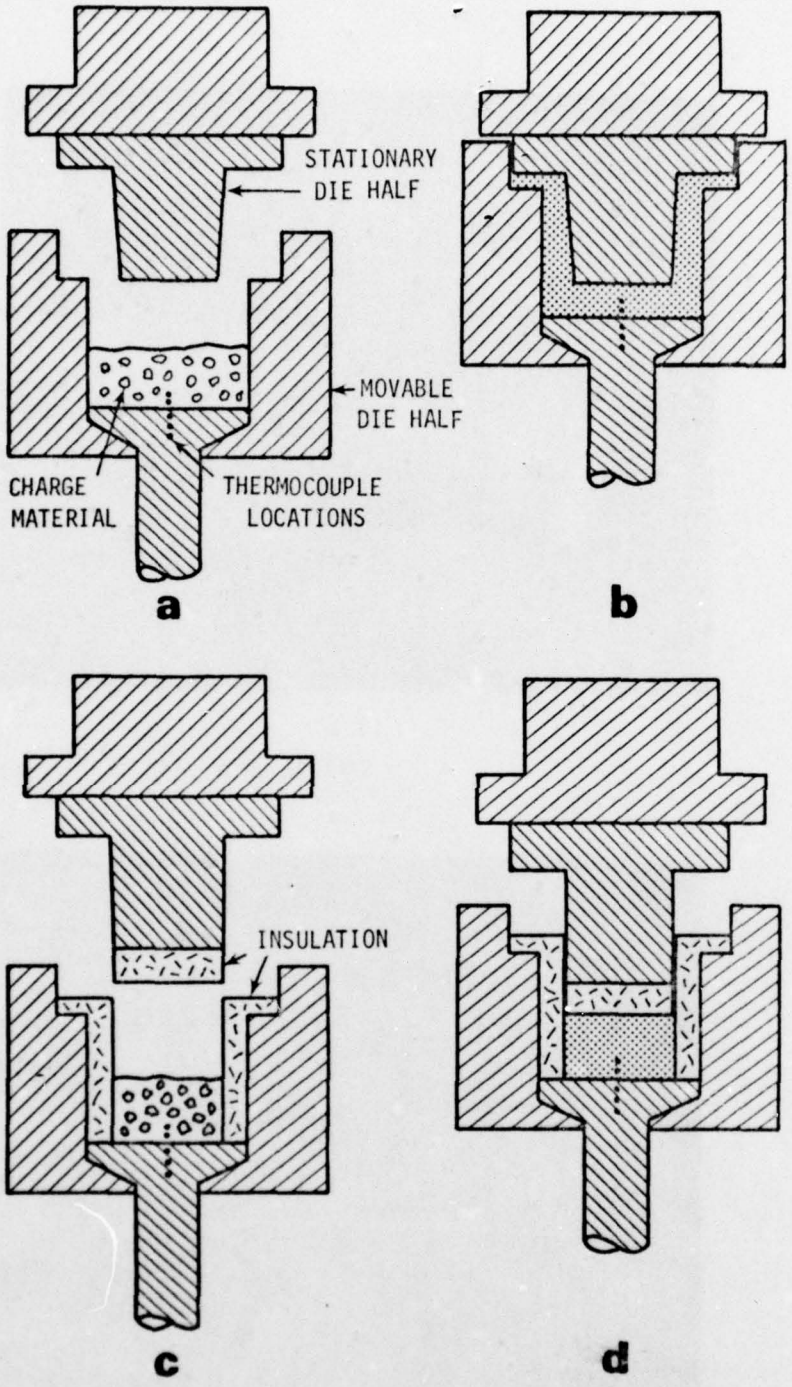
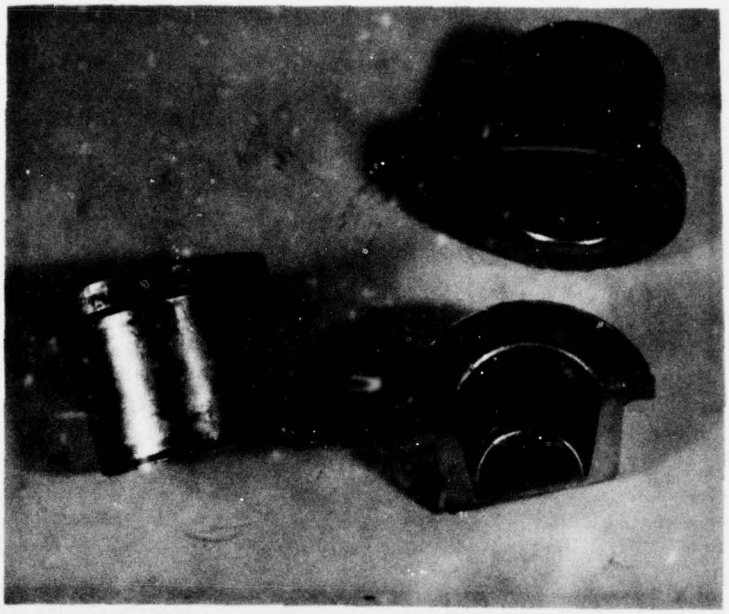
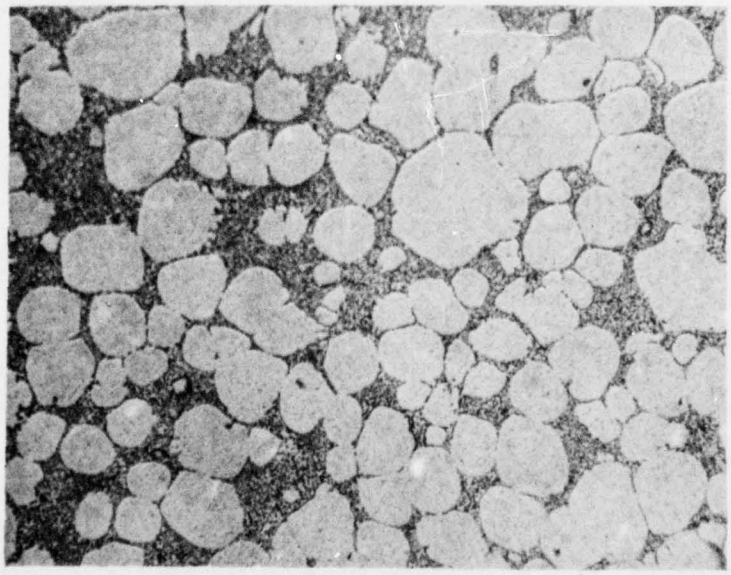


Figure 2. Schematic illustration of dies used in the forging apparatus; (a) and (b) refer to the cup shaped part, (c) and (d) refer to the unidirectionally solidified cylinders.



[a]



[b]

Figure 3 Photograph and a representative microstructure of Sn-15% Pb flanged cup parts. The volume fraction of solid in the initial charge was ∿0.5. (a) Photograph of two complete parts and a longitudinally sectioned part, (b) Internal microstructure at 100X.

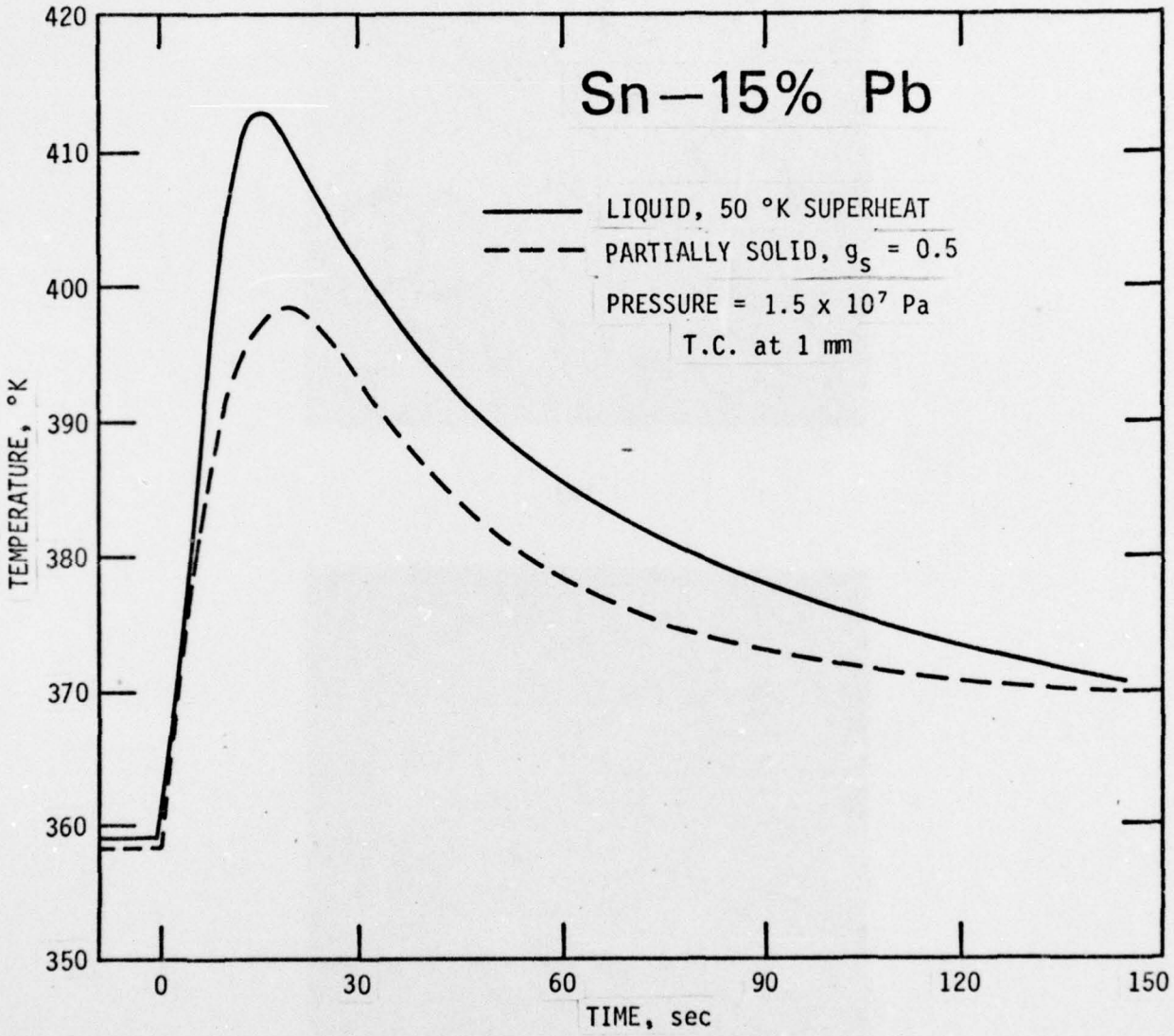
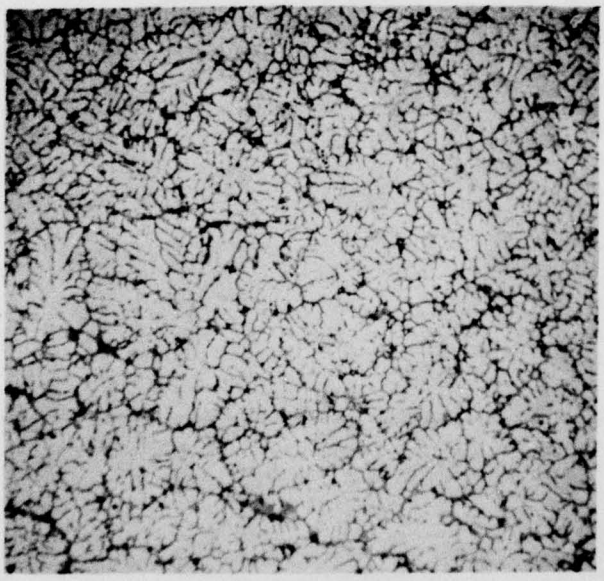


Figure 4. Die surface thermal response -- comparison between a superheated liquid and a partially solid initial charge. Flanged cup die cavity.

[a]



[b]

Figure 5 Microstructures of 6061 aluminum alloy parts at 55X magnification. (a) Thixoforged part at volume fraction solid of ∿0.65, (b) Part made with a completely liquid initial charge.

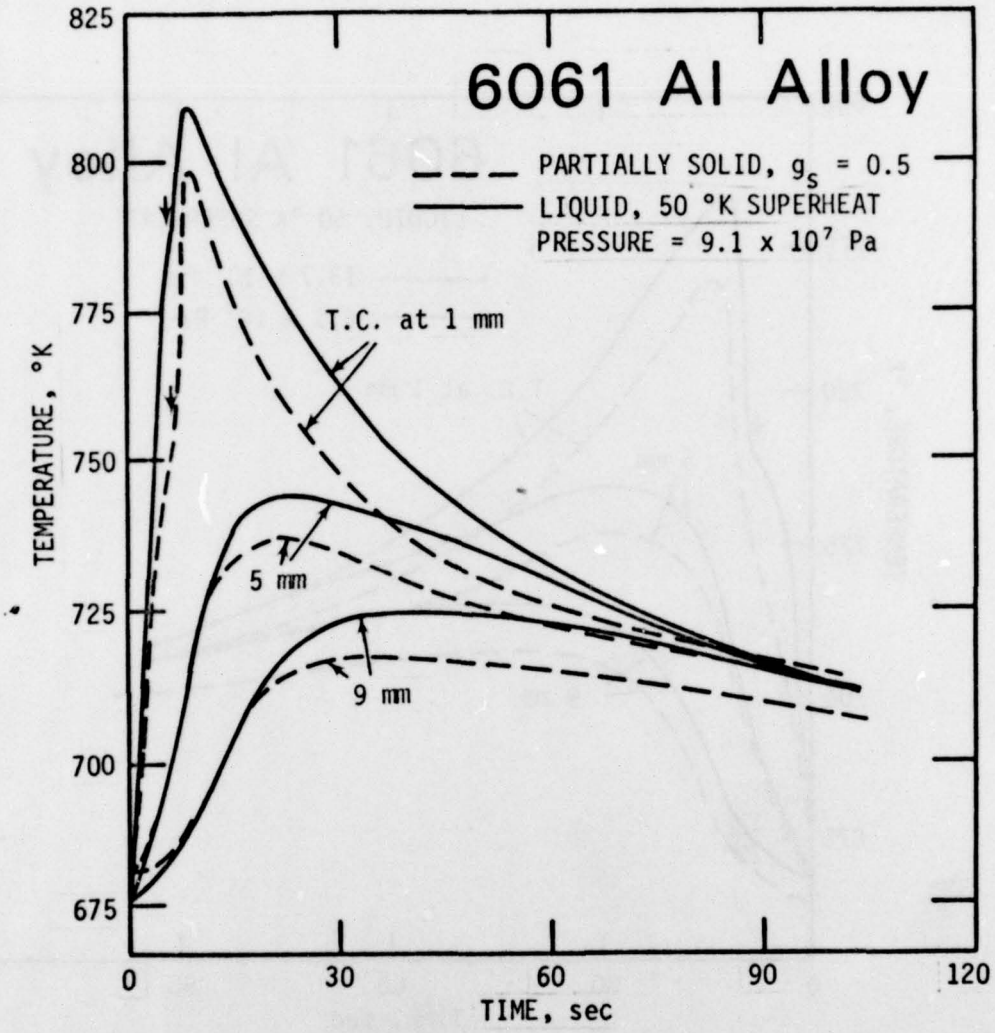


Figure 6. Die thermal response -- comparison between a superheated liquid and a partially solid initial charge. Flanged cup die cavity.

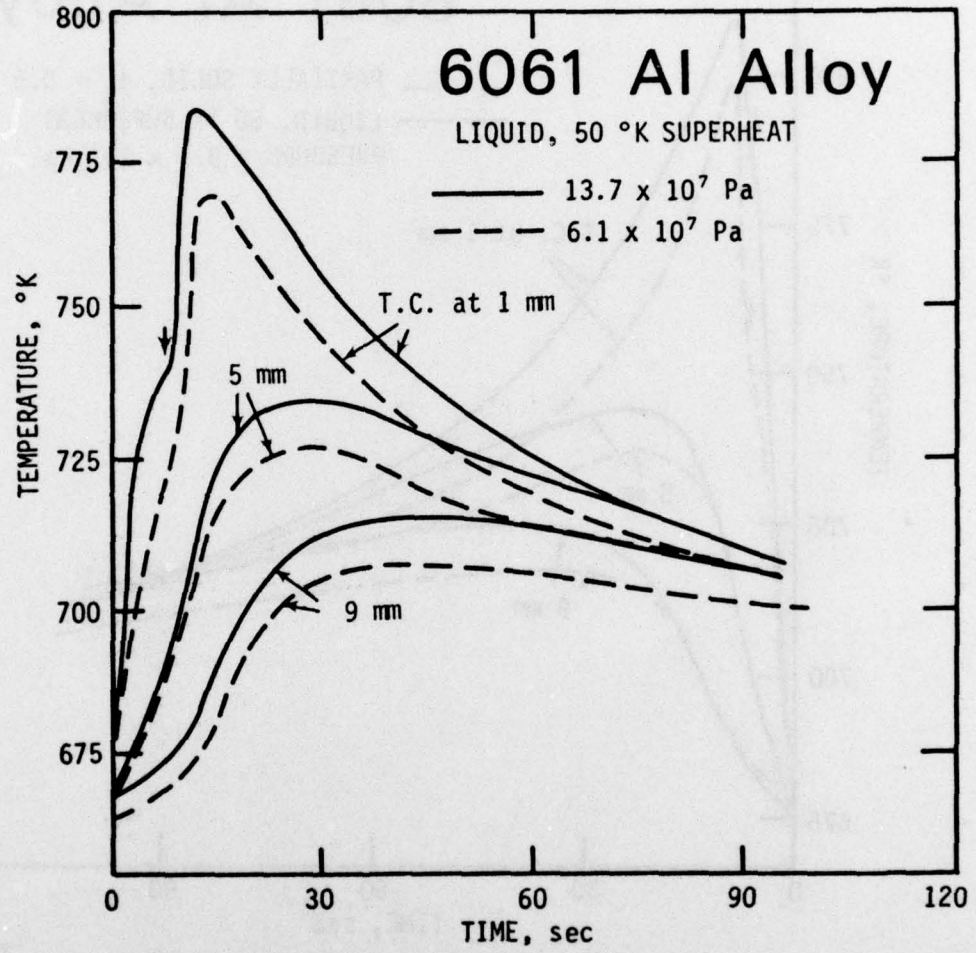


Figure 7. Effect of pressure on die thermal response during liquid forging. Note 13.7×10^7 and 6.1×10^7 Pa correspond to 20 and 45 tons in the hydraulic press, respectively. Flanged cup die cavity.

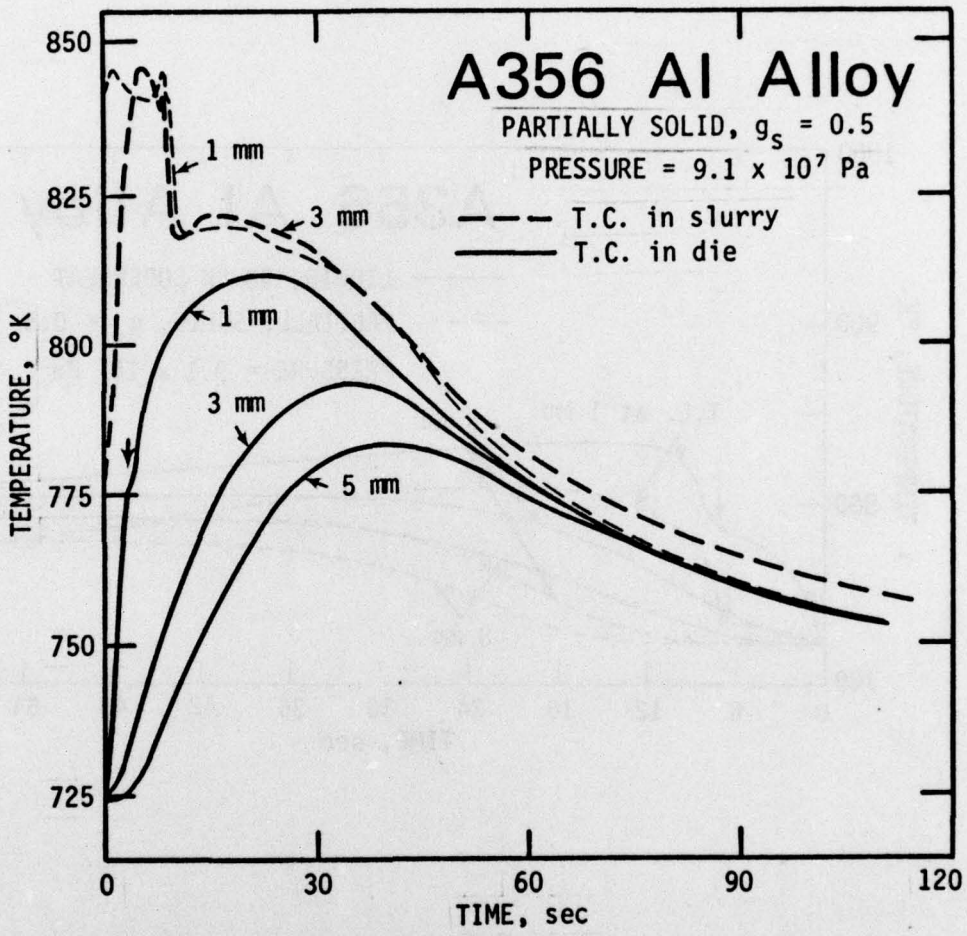


Figure 8. Composite of die and forging thermal response. Unidirectional die cavity.

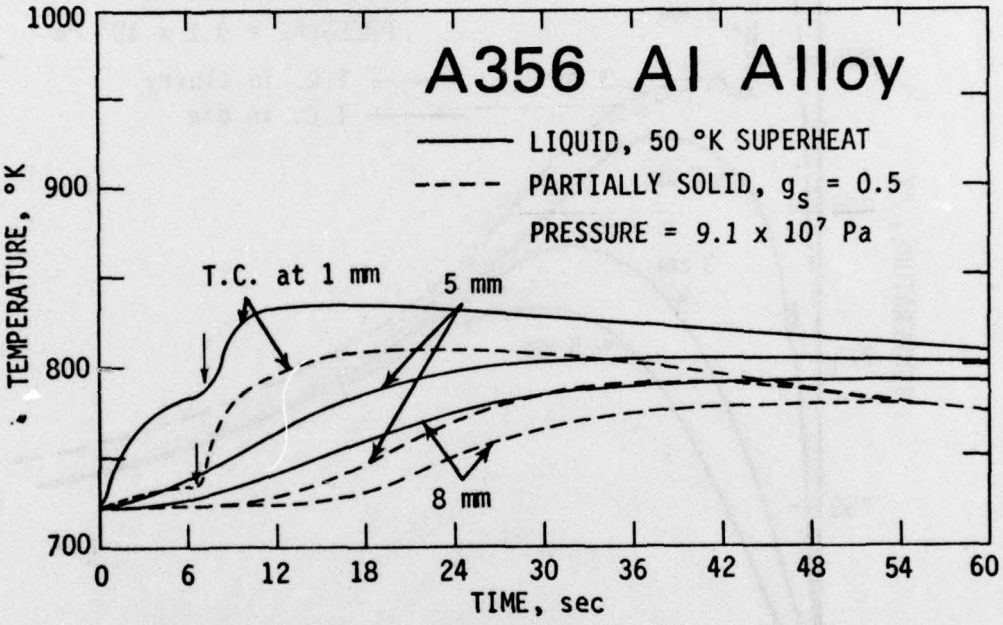
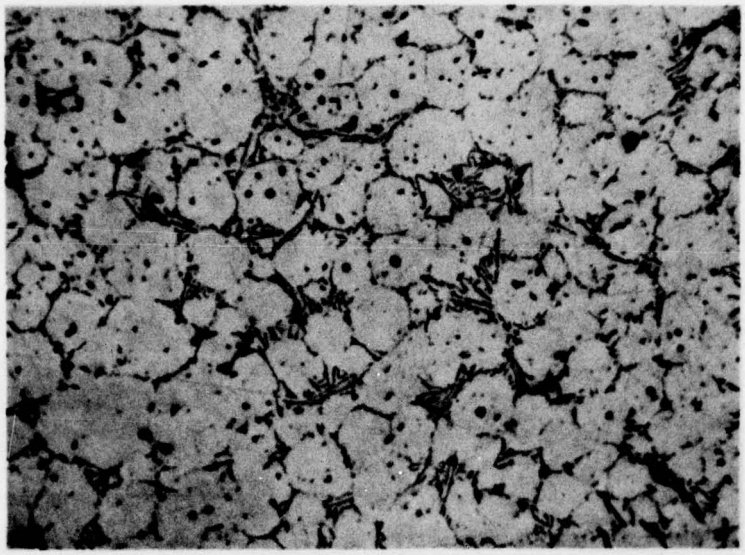
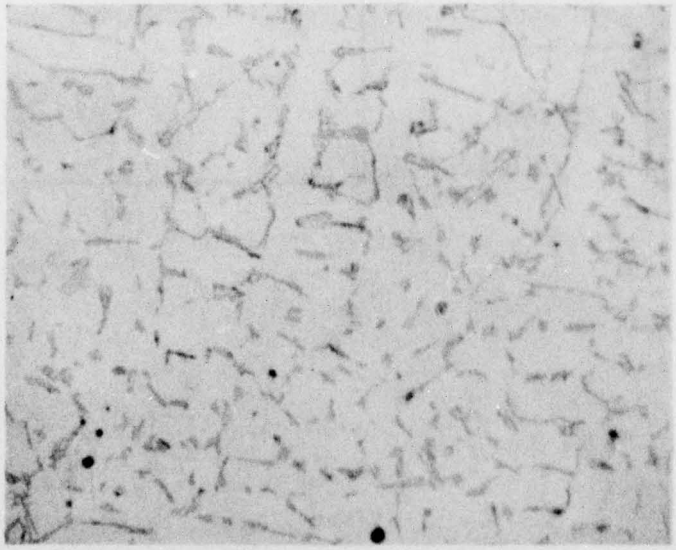


Figure 9. Die thermal response -- comparison between a superheated liquid and a partially solid initial charge. Unidirectional die cavity.



[a]



[b]

Figure 10 Microstructures of A356 aluminum alloy forgings made in the unidirectional die cavity. Magnification 100X. (a) Thixoforged part--initial volume fraction solid ∿0.6, (b) Part made from a superheated (∿ 50°K) liquid.

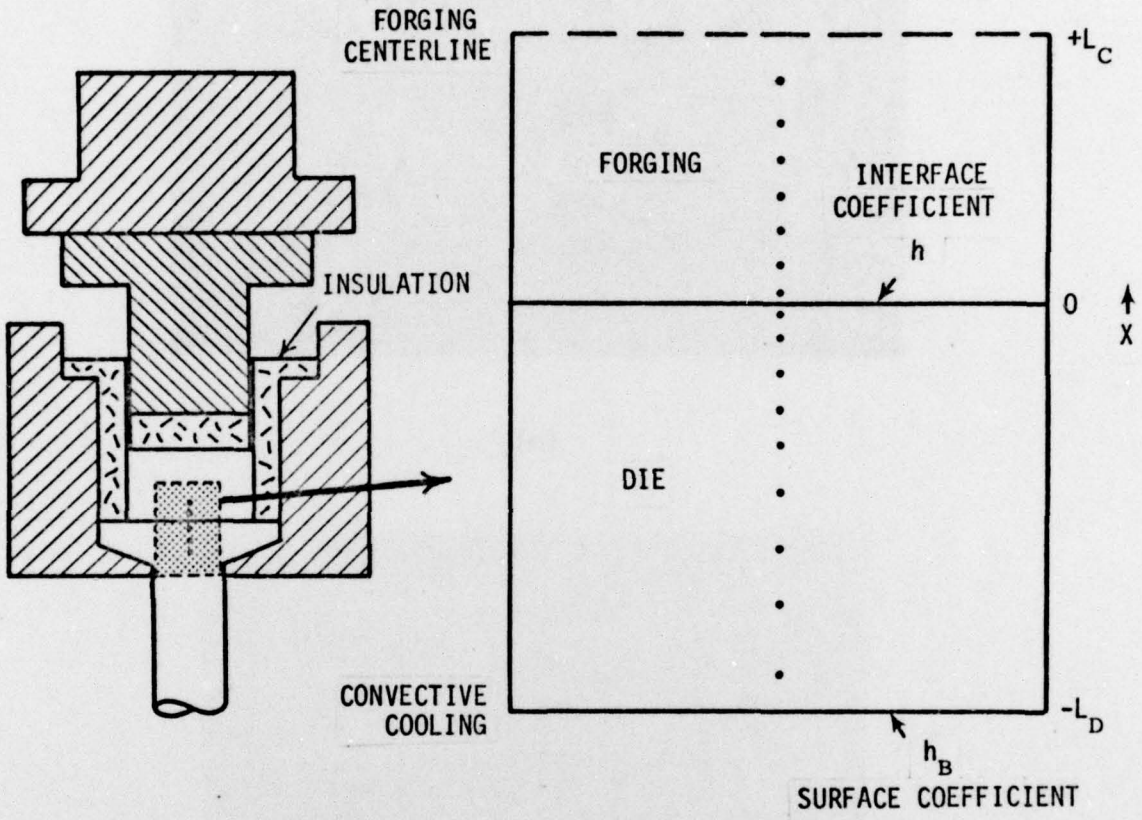


Figure 11. Schematic showing the volume element assumed to have a unidirectional thermal behavior. Expanded view shows positions of the nodes used in computer simulation studies.

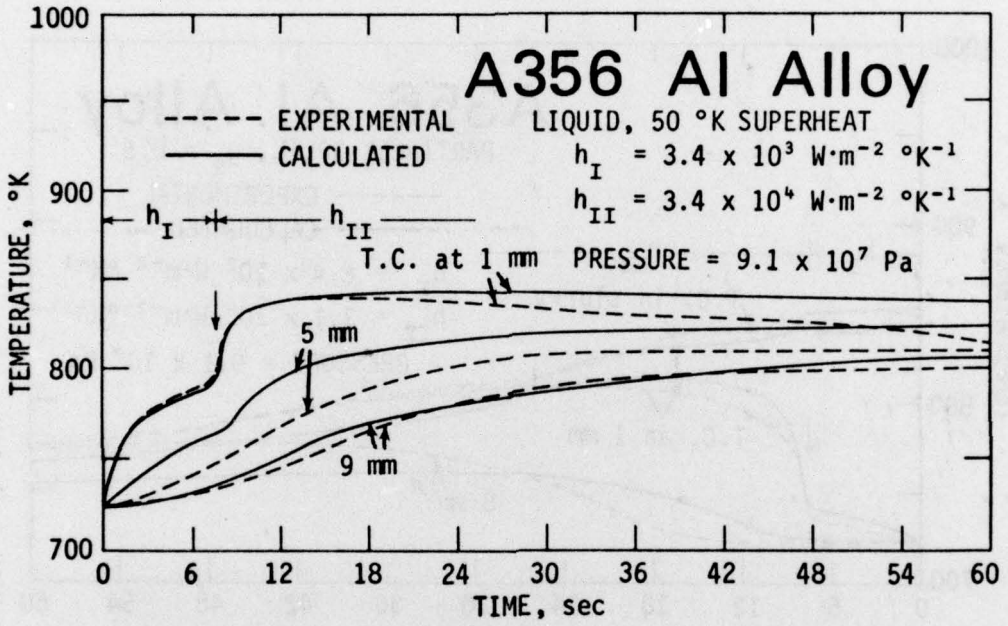


Figure 12. Die thermal response -- comparison between measured and calculated temperature profiles. Unidirectional die cavity.

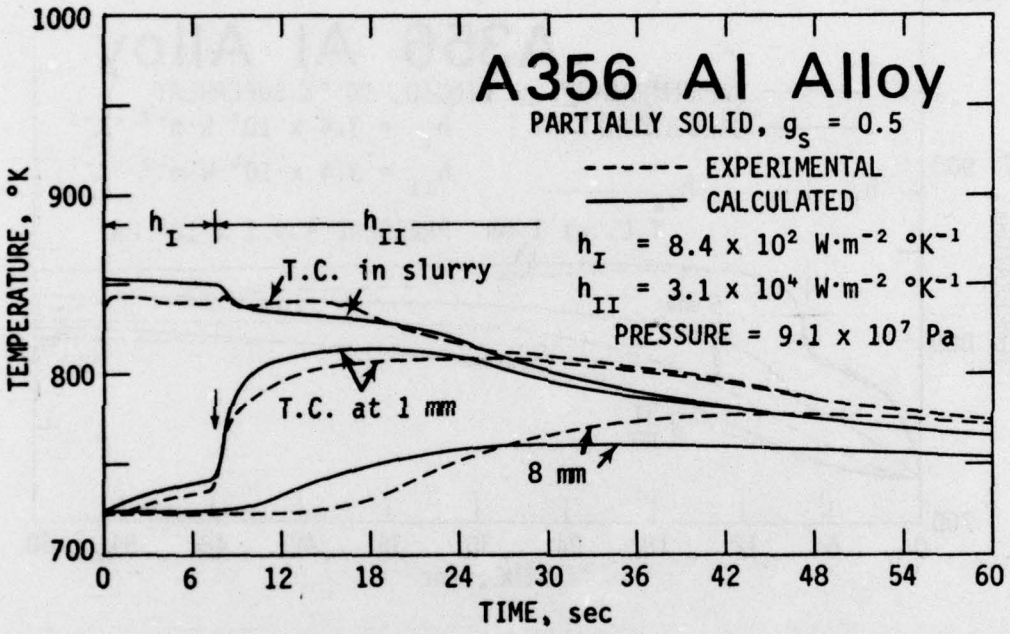


Figure 13. Composite of die and forging thermal responses -- comparison between measured and calculated temperature profiles. Unidirectional die cavity.

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